

SURFACE ROUGHNESS CHARACTERIZATION FOR A MINE AIRWAY IN THE SUNSHINE MINE

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ABSTRACT

The flow of air through a bare rock, underground airway is affected by the size and frequency of the micro- and macro-asperities of the rough surface. The focus of this study is to characterize this roughness using the coefficient of friction, the friction factor and the fractal dimension. The rough surfaces were identified by two sets of 177 and 78 transverse profiles measured by a laser profiler along the length of an underground airway at the Sunshine Mine, Idaho. Based on the measurements, the friction factor was estimated from Atkinson's equation and the coefficient of friction from the Moody diagram, and power series and variography were used for computing a fractal dimension for the airway surface. Significant conclusions are reached relating the effect of error in the measurement of cross-sectional and rubbing surface areas of a drift, on the estimated friction factor for the airway. The potential role of the fractal dimension as an alternative to the friction factor for characterizing the roughness of a mine airway is discussed.

INTRODUCTION

The roughness of the surface of an airway is described in different ways in the field of fluid dynamics. It is important to characterize the roughness of a surface in order to estimate the energy losses in the flow. The friction factor (k) and coefficient of friction (f) are frequently used parameters in the field of mine ventilation. The friction factor is calculated from Atkinson's equation, and a standard way of estimating a value for an underground airway is to use McElroy's table (McElroy, 1935). The coefficient of friction is another parameter which can be used to describe the surface roughness of an airway. The Moody diagram which is a function of the ratio of surface asperity to mean hydraulic diameter and the Reynolds number, is used to obtain this parameter.

Recently, the fractal dimension has been used to characterize surfaces of rocks and joints. For example, it is being used in the geological sciences for rockmass classification (Carr, 1990).

In this paper, a section of a mine ventilation airway at the Sunshine Mine, Idaho, is studied for the determination of the surface roughness parameters and fractal dimension, and a relationship between pressure loss, friction factor and fractal dimension is discussed.

ROUGH SURFACE DATA AND MEASUREMENTS

A set of data describing the surface of an underground airway was obtained using an Amberg Measuring Technique (AMT) 2000 tunnel laser profiler (Calizaya, et al., 1991). The survey was performed in a fan drift located on the 3100 level at the Sunshine Mine, Idaho. The layout of the fan drift and the location of the sections are shown in Figure 1. Two sections of this drift, 35.2 and 15.4 meters in length, were laser surveyed to obtain 177 and 78 transverse profiles respectively. A pressure and quantity survey was carried out in the former section and this was used for the calculation of k .

The tunnel profiler, was used to map the airway surface in the test sections. Each point on the transverse profile is represented by two parameters: a vertical angle and a radial distance. The profiles were taken every 20 centimeters over the test lengths in the airway. A schematic of the installation of the profiler and the angular positions of the longitudinal profiles is shown in Figure 2. For comparison purposes, the cross section was measured manually at 5 meter intervals in both the test sections. F1 to F8 in Table I, are the positions where manual measurements were made. In Table II, these measurements were numbered C1 to C4 for the 15.4-meter test section. Tables I and II compare the cross section -

areas and perimeters measured manually and by the laser profiler. The percentage differences are calculated with respect to the laser measurements.

Longitudinal profiles from -30° to 210° to the horizontal were plotted for each test section from the laser profiler data. Figure 3 shows the 210° profiles for the test sections. These longitudinal profiles are used to compute the coefficient of friction and the fractal numbers.

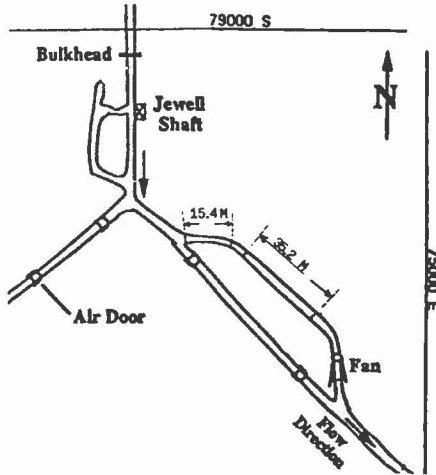


Figure 1. Layout of the Mine Drift

FRICTION FACTOR AND COEFFICIENT OF FRICTION

An important objective of this research is to compare the estimated airway values of k and f obtained when area and perimeter are measured using either conventional (hand taping) or laser techniques.

The friction factor, or Atkinson's k factor, is an empirical factor used to predict pressure drops in mine airways. Atkinson's equation is used to calculate this factor. The relationship between Darcy's coefficient of friction and Atkinson's friction factor is given by:

$$f = \frac{2k}{\rho} \quad (1)$$

where, ρ is the density of air.

For standard air conditions ($\rho = 1.2 \text{ kg/m}^3$) this equation yields $f = 1.667k$.

Alternatively, f can be determined from the Moody diagram based on two parameters: the surface roughness, characterized by the asperity height to hydraulic diameter ratio, and the Reynolds

number. Both f and k were calculated using the following airway conditions in the test section I:

Pressure drop, $[\Delta p] = 11.45 \text{ Pa}$
 Quantity of air, $[Q] = 27.4 \text{ m}^3/\text{sec.}$
 Airway length, $[L] = 35.2 \text{ m}$

Friction Factor

Based on Atkinson's equation, this factor is given by:

$$k = \frac{\Delta p A^3}{Q^2 \text{ Per } L} \quad (2)$$

Using the average area (A) and perimeter (Per) from the 177 transverse laser profiles, namely 6.614 m^2 and 9.955 m , this equation yields $k = 0.0126 \text{ kg/m}^3$.

The best estimate of the actual rubbing surface area ('Per L ' in equation 2) can be obtained from the laser profiler data. This was determined using the SURFER computer software package. For the 35.2 m length of the drift, the rubbing surface area was computed to be equal to 396.72 m^2 . Based on this area, the best estimate of the perimeter is equal to 11.27 m which yields a k factor equal to 0.0111 kg/m^3 when an area of 6.614 m^2 is used. This is 11.9% less than the k factor calculated from the average of the 177 profiles.

The k value of 0.0111 kg/m^3 is compared in Table III with the estimated friction factors obtained using each of the eight manual-measurements as representative of the average airway dimensions. It is typical in normal ventilation practice to take only one manual-measurement in such a short length of airway. It can be seen that if any of the eight k values, based on the manual measurements, are used to estimate the k value for the airway, a considerable error would occur, typically overestimating the k value.

Coefficient of Friction

In this case, the coefficient of friction, f , was determined based on the following parameters: mean asperity height to hydraulic diameter ratio and Reynolds number. The longitudinal profiles produced from laser data were used to determine the asperity height. The average asperity height, e , was determined by normalizing and averaging the asperity heights of nine longitudinal profiles. For example, the profile which is inclined 150° to the positive x -axis from Section I, has a minimum asperity height of 0.733 meters , and this was subtracted from all the values in order to obtain the real asperity heights. This profile has a mean

TABLE I. Comparison of Area and Perimeter Using Manual and Laser Profiling Methods for Section I.

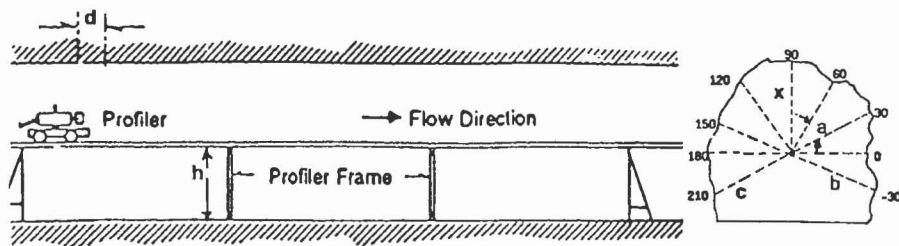
Station	Area(m ²)		% Difference Area	Perimeter(m)		% Difference Perimeter
	Manual	Laser		Manual	Laser	
F1	6.917	6.726	2.84	10.526	10.091	4.31
F2	7.80	7.879	-1.00	11.176	10.669	4.75
F3	7.756	7.480	3.69	11.158	10.408	7.21
F4	6.821	6.812	0.13	10.448	10.131	3.13
F5	6.778	7.084	-4.32	10.426	10.590	-1.55
F6	5.700	5.566	2.41	9.552	9.219	3.61
F7	7.499	7.381	1.60	10.954	10.561	3.72
F8	6.753	6.587	2.52	10.408	10.278	1.27
F _{ave} *	7.004	6.939	0.94	10.581	10.243	3.30

*Average area and perimeter from 177 profiles are 6.614 m² and 9.955 m.

TABLE II. Comparison of Area and Perimeter Using Manual and Laser Profiling Methods for Section II.

Station	Area(m ²)		% Difference Area	Perimeter(m)		% Difference Perimeter
	Manual	Laser		Manual	Laser	
C1	6.097	6.588	7.45	9.878	9.714	1.69
C2	6.477	6.299	2.82	10.184	9.677	5.24
C3	5.796	5.397	7.39	9.632	9.064	6.27
C4	6.948	6.973	-0.36	10.544	9.868	6.85
C _{ave} *	6.328	6.314	0.22	10.06	9.581	5.00

*Average area and perimeter from 78 profiles are 6.252 m² and 9.666 m.



- h= Height of the Instrument
- x= Offset
- d= Longitudinal Step
- a= Angular Step
- b= Starting Direction
- c= Ending Direction

Figure 2. Schematic Drawing of Installation of AMT Profiler

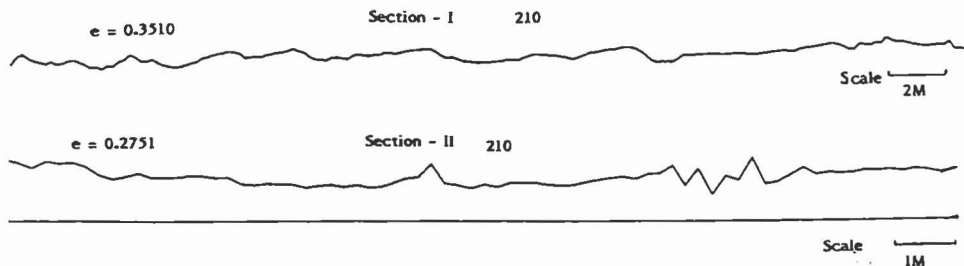


Figure 3. Longitudinal profiles at 210° angular position.

TABLE III. Estimation and Comparison of the Friction Factors Using Manual Measurement and Laser Profiling.

Station	k_{manual}	k_{laser}	% Difference
F1	0.0136	0.0111	22.5
F2	0.0184	0.0111	65.8
F3	0.0181	0.0111	63.1
F4	0.0132	0.0111	18.9
F5	0.0129	0.0111	16.2
F6	0.0084	0.0111	-24.3
F7	0.0167	0.0111	50.5
F8	0.0128	0.0111	15.3
F_{ave}	0.0141	0.0111	27.0
Average of 177 profiles	0.0126	0.0111	13.5

asperity height of 0.2216 meters. The mean asperity height of the nine profiles was taken and averaged to get a representative asperity height. Three quarters of this quantity represents the true asperity height, which was 0.2439. This is because the floor of the drift was assumed to have a linear profile with a zero asperity height. The hydraulic diameter, d , was determined by dividing four times the area by the perimeter.

a. Test Section I:

Based on the best estimate of area and perimeter, the average hydraulic diameter was calculated to be 2.348 meters. The e/d ratio from these parameters was found to be 0.1039. The Reynolds number was calculated from the equation $N_{Re} = 67,280 dv$ (Hartman, 1982). For $v=4.143$ m/sec and $d=2.348$ meters, this number was estimated to be 654,500.

For these values, using the Moody Diagram the coefficient friction was calculated to be 0.026.

In developed turbulent flow, this coefficient can also be obtained from Von Karman's equation:

$$1/\sqrt{f} = 2.276 - 4\text{Log}_{10}(e/d) \quad (3)$$

which yields a value of 0.0259.

Table IV shows, using the manual measurements, the estimates of the coefficient of friction determined from the Moody diagram or Von Karman's equation (which yield the same values), and compares them with the best estimate of f calculated above.

b. Test Section II:

The best estimate of the rubbing surface area for this section was 189.57 m², and from this the equivalent perimeter for the 15.4 m length of airway was calculated to be 12.309 m. The mean hydraulic diameter of the airway using an average area of 6.252 m² determined from the 78 profiles, is 2.032 m. From the nine longitudinal profiles obtained, the true asperity height was calculated to be 0.1643 m. From this the e/d ratio is equal to 0.0809. The best estimate of f from Von Karman's equation is 0.0226. Table V shows a comparison of coefficients of friction calculated from the manual and laser measurements.

The error between the estimated f value for the airway, obtained from a single manual measurement, and the best estimate of f , is considerably less than that obtained for the k values in section I. Instead of the large overestimation of k , Tables IV and V show a small underestimation of the f value. It can be seen that the average % difference between the f values is greater in Table V. This might be due to a lower e/d ratio for test section II.

FRACTAL DIMENSION

There are two methods to estimate the fractal dimension for any set of data. One of these is based on the measurement process called the divider or compass technique (Mandelbrot, 1967). The other is based on stochastic notions, namely: variography and the power spectrum. The fractal dimension, D , can be determined by the formula (Carr & Benzer, 1991):

$$D = 2 - \text{Abs}(H) \quad (4)$$

where,

H is the slope of the regression fit of the logarithm of semi-variogram on the y axis and logarithm of lag distance on the x axis. This parameter can also be determined by the power series method. The formula is given by (Mandelbrot, et al, 1984):

$$D = 2.5 - \text{Abs}(\beta/2) \quad (5)$$

where,

β is the slope of the regression fit of the logarithm of power values on the y axis to the logarithm of the frequency on the x axis (Konduri, et al, 1992) Both methods for determining the fractal dimension (variography and power spectrum) are mathematically similar, and, theoretically, give the same results. This can be explained from the relationship given by Saupe (1987):

$$\beta = 2H + 1 \quad (6)$$

TABLE IV. Estimation and Comparison of the Coefficients of Friction Using Manual Measurement and Laser Profiling for Section I.

Station	d	e/d	N_{Re}	f_{manual}	f_{laser}	% Difference
F1	2.629	0.0928	732800	0.02437	0.026	-6.1
F2	2.794	0.0873	778800	0.02358	0.026	-9.1
F3	2.780	0.0880	774900	0.02368	0.026	-8.7
F4	2.611	0.0934	727800	0.02445	0.026	-5.8
F5	2.600	0.0938	724700	0.02451	0.026	-5.5
F6	2.387	0.1022	665400	0.02570	0.026	-1.0
F7	2.740	0.0891	763750	0.02384	0.026	-8.1
F8	2.586	0.0943	720800	0.02458	0.026	-5.3
F_{ave}	2.640	0.0921	735900	0.02427	0.026	-6.5
Average of 177 profiles	2.658	0.0918	740900	0.0245	0.026	-5.6

TABLE V. Estimation and Comparison of the Coefficients of Friction Using Manual Measurement and Laser Profiling for Section II.

Station	d	e/d	f_{manual}	f_{laser}	% Difference
C1	2.469	0.0666	0.02051	0.0226	-9.25
C2	2.544	0.0646	0.02020	0.0226	-10.62
C3	2.407	0.0683	0.02077	0.0226	-8.1
C4	2.636	0.0624	0.01986	0.0226	-12.12
C_{ave}	2.4006	0.0685	0.02080	0.0226	-7.96
Average of 78 profiles	2.517	0.0635	0.0200	0.0226	-11.5

In practice, the accuracy of this relationship depends on the window size, which is discussed by Konduri, et al. (1992).

Section I

a. Semi-Variogram:

Table VI shows the estimated fractal numbers for the nine profiles investigated. The fractal dimensions in this table indicate some uniformity in the variation of the surface profiles along the drift. The last three profiles have significantly lower fractal numbers and these differences can be observed in the corresponding longitudinal profiles.

b. Power Spectrum:

Spectral analysis was carried out on all of the nine profiles. The profiles of the power spectrum showed spikes in the low frequency region corresponding to high power values. These can be interpreted as infrequently occurring asperities. These were

neglected in the slope computations of the spectrum. The influence of these spikes can be considerable, and it was observed that elimination of such points from the power series gave consistent values for the fractal number. In the evaluation, a window of size 128 was used. Results are tabulated in Table VI, which show a good comparison to those obtained using the semi-variogram method.

TABLE VI. Fractal Dimension for Section I.

Angular Position	Variography	Spectral Analysis
-30°	1.651	1.685
0°	1.589	1.755
30°	1.563	1.670
60°	1.596	1.645
90°	1.714	1.750
120°	1.609	1.620
150°	1.305	1.365
180°	1.480	1.410
210°	1.475	1.405

Section II

In this section the nine profiles were analyzed in a similar fashion to obtain the fractal numbers. The results are shown in Table VII. From this table, it can be observed that the differences between the fractal dimensions of corresponding profiles are quite high. This is due to two reasons, firstly, the relative variation in the profiles is much higher in Section II than in Section I. Secondly, since there were only 78 profiles measured in this section and a window size of 64 was used in the power series for the analysis, the fractal dimension results are less reliable.

TABLE VII. Fractal Dimensions for Section II.

Angular Position	Variography	Spectral Analysis
-30°	1.667	1.705
0°	1.649	1.735
30°	1.624	1.845
60°	1.522	1.385
90°	1.596	1.605
120°	1.345	1.140
150°	1.645	1.765
180°	1.737	1.995
210°	1.805	1.885

DISCUSSION AND CONCLUSIONS

It is clear that the laser profiler results give a more accurate measurement of the area and perimeter at a particular cross section in a mine airway, than does the standard manual taping method. The difference does not appear to be that significant when comparing values at the same location (Tables I & II). However, the ability of the laser profiler to measure many more cross sections accurately, makes it possible to estimate overall measurements of rubbing surface and cross-sectional areas for a length of an airway, which is much more accurate than that obtained by the typical methods currently in use.

The k value, obtained using all the laser profiles (177 cross sections) to provide the best estimates of actual rubbing surface and cross-sectional areas for the test section, was considerably lower than those determined from manual measurements. The differences ranged from +65% to -24% (Table III), where most of the differences show that the estimated k values from the manual readings were too high.

It is interesting to observe that the difference between the respective values of f is considerably

less than that for k and is in the opposite direction i.e. the manual measurements underestimate the f values (compare Tables III, IV and V). This is primarily due to the use of area and perimeter in the respective equations to determine f and k . If a laser profiler is not available, these results indicate that if the f value is computed from Equation 3 and the k value from Equation 1 this will result in a closer estimate of the actual value of k than using Equation 2. These results indicate that the published k factors, to date, may be too high. It is recommended that mines requiring accurate k or f values for future ventilation planning, at least consider renting a laser profiler to accurately measure airway profiles during a pressure quantity survey.

The fractal numbers obtained from both the variogram and the power series are found to be within a smaller range for Section I than for Section II. The fractal numbers obtained from variography are more consistent with each other than are the results obtained from spectral analysis. The larger the window width, the more consistent are the results. The variogram results are believed to be more accurate, not just because the values are more consistent with each other, but because all the data are used when the variograms are calculated. In the power spectrum method, due to the restrictions of the Fast Fourier series, for Section I, out of 177 observations, only 128 were used. Additional information that can be obtained from the semi-variogram is periodic variation, which is observed every 2.0 meters, coinciding with the length of a development round at the Sunshine Mine.

The fractal dimension reflects the self similarity of a profile or a surface. The results tabulated for the fractal dimension show that there is a sudden drop in the values from the profile at 150° to 210° angular position for Section I. This reveals that the jaggedness in these profiles is very low and shows higher self-similarity. Similarly, the profiles at angles 180° and 210° for Section II have very high fractal numbers. This is not obvious from visual inspection of these profiles. The fractal dimension is very useful in finding such properties in the surfaces both at micro- and macro-scopic levels.

Although the results obtained in this study are in agreement with those generated by Banik at the laboratory level (Banik, 1990), it is clear that two sets of readings are not sufficient to establish any concluding relationship on this matter. Therefore, it is recommended that the study be repeated at many different mines, for a variety of surface roughnesses and flow rates, in order to determine a relationship between pressure loss and fractal dimension.

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